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硕 士 学 位 论 文

CFD 模拟中的气体辐射换热计算研究

Investigation of Gas Radiation Heat Transfer in CFD  
Simulation

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## 摘要

在工业生产中, 辐射换热通常是气缸、燃烧室、炉膛等燃烧设备中的主要的换热方式之一。燃烧室里是高温高压的燃烧气体, 存在辐射换热和对流换热; 对于大型的燃烧设备, 辐射换热往往占主导地位。精确地模拟燃烧室内的气体辐射换热对燃烧室内总的热平衡和燃烧室局部过热分析至关重要。同样, 随着航天、军工等信息技术的发展, 火箭尾喷焰探测、目标红外的捕捉、飞行器的热防护设计等使得气体辐射的研究越来越重要。因此准确而有效的计算气体辐射换热对诸多工程和研究领域都非常重要。然而, 由于热辐射强度一方面空间上随位置和角度变化; 一方面, 水蒸气、二氧化碳等极性分子气体不像固体那样发射随波长连续变化的辐射, 而是依赖于波长, 选择性吸收和发射热辐射; 从而导致精确模拟气体辐射换热的难度加大。

现阶段气体辐射换热的计算方法主要有实验法和光谱法。由于高温高压条件下, 实验成本非常高, 同时实验结果易受实验设备的影响, 使得高温实验的进行有一定难度。CFD 数值模拟发展多年, 已经广泛应用于工业及科学领域, 其精度已经能够全部或部分取代实验。气体辐射不同于其它物质的关键之处在于气体辐射具有很强的光谱选择性, 吸收发射的光谱主要集中在一些特定的波长间隔(带)内。整个热辐射光谱范围内有数万个波数, 根据波数范围可以分成多个谱带, 谱带内则集中了成千上万根谱线。同时准确地计算气体辐射换热需要高分辨率的光谱辐射特性参数(主要包括谱线强度、谱线位置、谱线形状以及谱线半宽)。于是在 CFD 计算中采用精确的谱带模型法的计算量非常大, 且过于费时。本文针对气体辐射的研究主要采用以下两种方法: 1、统计窄带 SNB 模型; 2、灰体辐射近似法。方法 2 为常规的灰体辐射假设, 不过灰体辐射系数不是一个常数, 而是气体组分、温度和燃烧设备几何的函数。通过 CFD 软件的用户子程序来计算这个辐射系数。基于实验所得并公开发表的气体发射率而编制的灰体吸收系数子程序。分别用以上两种方法对气体辐射换热工况进行分析并将结果与公开发表的文献数据进行验证与校核。

**关键字:** 气体热辐射; 统计窄带波谱模型; 气体灰体辐射模型; CFD 模拟

## ABSTRACT

During industrial production, radiation heat transfer is usually one of the main ways of heat transfer in cylinders, combustors and furnaces. There is radiation heat transfer and convection heat transfer in combustors filled with high temperature and high pressure burning gases. For large-scale combustion equipments, radiation heat transfer tends to dominate. So it is important to accurately simulate thermal radiation to calculate the total heat balance and regional overheating analysis in combustion equipments. Similarly, with the progress of the industries such as aerospace and military industries, there are problems such as jet tail flame detection of rockets, the capture of infrared target and the thermal protection design of aircraft. All make the research of gas radiation more and more important. Therefore, it is vital to calculate the radiation heat transfer of gases accurately and effectively for the importance in so many fields. However, owing to spatial variation of the heat transfer intensity with position and angle, the polar molecules such as water vapor and carbon dioxide do not emit radiation with the intensity variation with wavelength continuously, instead it depends on the wavelength and selectively absorb and emit thermal radiation, which adds the difficulty of accurate simulation of radiation heat transfer.

At present there are two main methods of determining radiation heat transfer: experimentation and spectrum integration method. Usually the experiment cost is high for experiments in high temperature and high pressure condition, the results are strongly affected by the test device at the same time, which causes some difficulty in experiment of high temperature condition. Since CFD has been developing for many years, it is widely used in industry and science nowadays, the accuracy is enough to substitute experimentation at least partially. The gas radiation differs from solid for its strong selectivity in spectrum, the absorption and emission spectrum is mainly focused in some specific wavelength intervals. There are tens of thousands of wave number in the whole thermal radiation spectrum; according to the range of wave number it can be divided into multiband, and there are hundreds of thousands of spectrum lines focused on these bands. To calculate the radiation heat transfer of

gases accurately, we also need characteristic parameters of radiation with high resolution (mainly includes spectral line intensity, spectral line position, spectral line shape and spectral line half-width). As a result, the spectrum method needs tremendous calculation time which makes it only feasible in academic research. In this article, the research on gas radiation mainly adopts the following two approximation methods that could be used for industry: 1. spectral band model method. 2. gray body method. The spectral band model in method 1 is based on the published absorption coefficient of gas, the absorption coefficients of the whole spectral range is segmented according to the wavelength interval. Also it can be divided into narrow or wide bands. The gray body radiation model in method 2 uses subroutine to calculate the gray absorption coefficient which is a function of gas composition, temperature and equipment geometry. The gray body absorption coefficients are programmed on the basis of gas emissivity which has been experimented and published. Afterwards we'll analyze the working conditions of gas radiation heat transfer with these two methods separately, and finally verify the results with the published data.

**Key Words:** Gas Thermal Radiation; Narrow Band (Wide Band); Gray Model; CFD Simulation

## 主要变量名列表

$A$  面积,  $m^2$ ; 有效带宽

$b$  谱线半宽,  $m^{-1}$

$b_c$  气体碰撞增宽半宽,  $m^{-1}$

$E$  单位面积发射率,  $W/m^2$

$E_{b,\lambda}$  黑体光谱发射功率

$E_b$  黑体全波长发射功率

$K_a$  吸收系数,  $m^{-1}$

$K_s$  散射系数,  $m^{-1}$

$G$  辐照强度,  $W/m^2$

$h$  普朗克常数,  $J \cdot s$

$I$  辐射强度,  $(W/m^2 \cdot sr)$

$k$  波尔兹曼常数,  $J \cdot K^{-1}$

$k$  谱带平均吸收系数,  $cm^{-1} \cdot atm^{-1}$

$L$  特征长度,  $m$

$M_k$  总的吸收量,  $W$

$M_\varepsilon$  总的发射量,  $W$

$P$  压强,  $Pa$

$q_{net}$  净辐射换热密度,  $W/m^2$

$Q$  外界投射到表面的总能量,  $W$

$Q_a$  物体吸收能量,  $W$

$Q_\rho$  物体反射能量,  $W$



$Q_r$  物体投射能量,  $W$

$S$  谱线强度,  $cm^{-1} \cdot (molec \cdot cm^{-2})^{-1}$

$s$  路径长度,  $m$

$T$  温度,  $K$

$W$  为等效谱线宽度

$\alpha$  吸收率

$\varepsilon$  发射率

$\Delta\varepsilon$  气体混合修正因子

$\bar{\varepsilon}$  平均发射率

$\beta$  谱线的重合度参数

$\eta$  波数,  $cm^{-1}$

$\Delta\eta$  谱线间隔,  $m^{-1}$

$k$  吸收系数,  $m^{-1}$

$\bar{k}$  平均吸收系数,  $m^{-1}$

$\lambda$  波长,  $\mu m$

$\mu$  黏度,  $kg/(sm)$

$\rho$  密度, 反射率

$\sigma$  波尔兹曼常数; 波数,  $cm^{-1}$

$\sigma_c$  谱线中心的波数

$\phi$  方位角,  $rad$

$\tau$  透射率

$\Omega$  空间立体角,  $sr$

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